US012295682B2

(12) **United States Patent**
Kostrzewski

(10) **Patent No.: US 12,295,682 B2**
(45) **Date of Patent: *May 13, 2025**

(54) **ROBOTIC SURGICAL SYSTEMS**

(71) Applicant: **KB MEDICAL, SA**, Audubon, PA (US)

(72) Inventor: **Szymon Kostrzewski**, Lausanne (CH)

(73) Assignee: **Globus Medical, Inc.**, Audubon, PA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

This patent is subject to a terminal disclaimer.

(21) Appl. No.: **18/482,395**

(22) Filed: **Oct. 6, 2023**

(65) **Prior Publication Data**

US 2024/0050171 A1 Feb. 15, 2024

Related U.S. Application Data

(63) Continuation of application No. 17/352,505, filed on Jun. 21, 2021, now Pat. No. 11,806,100, which is a (Continued)

(51) **Int. Cl.**

A61B 34/30	(2016.01)
A61B 34/00	(2016.01)
A61B 34/10	(2016.01)
A61B 90/11	(2016.01)
B25J 9/16	(2006.01)
B25J 15/00	(2006.01)
A61B 34/20	(2016.01)

(52) **U.S. Cl.**

CPC ***A61B 34/30*** (2016.02); ***A61B 34/10*** (2016.02); ***A61B 34/76*** (2016.02); ***A61B 90/11*** (2016.02); ***B25J 9/1633*** (2013.01); ***B25J 9/1679*** (2013.01); ***B25J 15/0019*** (2013.01); *A61B 2034/107* (2016.02); *A61B 2034/2051* (2016.02); *A61B 2034/2055* (2016.02); *A61B 2034/304* (2016.02); *B25J 9/1602* (2013.01); *Y10S 901/09* (2013.01)

(58) **Field of Classification Search**

CPC A61B 34/30; A61B 34/10; A61B 34/76; A61B 90/11; A61B 2034/107; A61B 2034/2051; A61B 2034/2055; A61B 2034/304; B25J 9/1633; B25J 9/1679; B25J 15/0019; B25J 9/1602; Y10S 901/09

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,150,293	A	4/1979	Franke
5,246,010	A	9/1993	Gazzara et al.

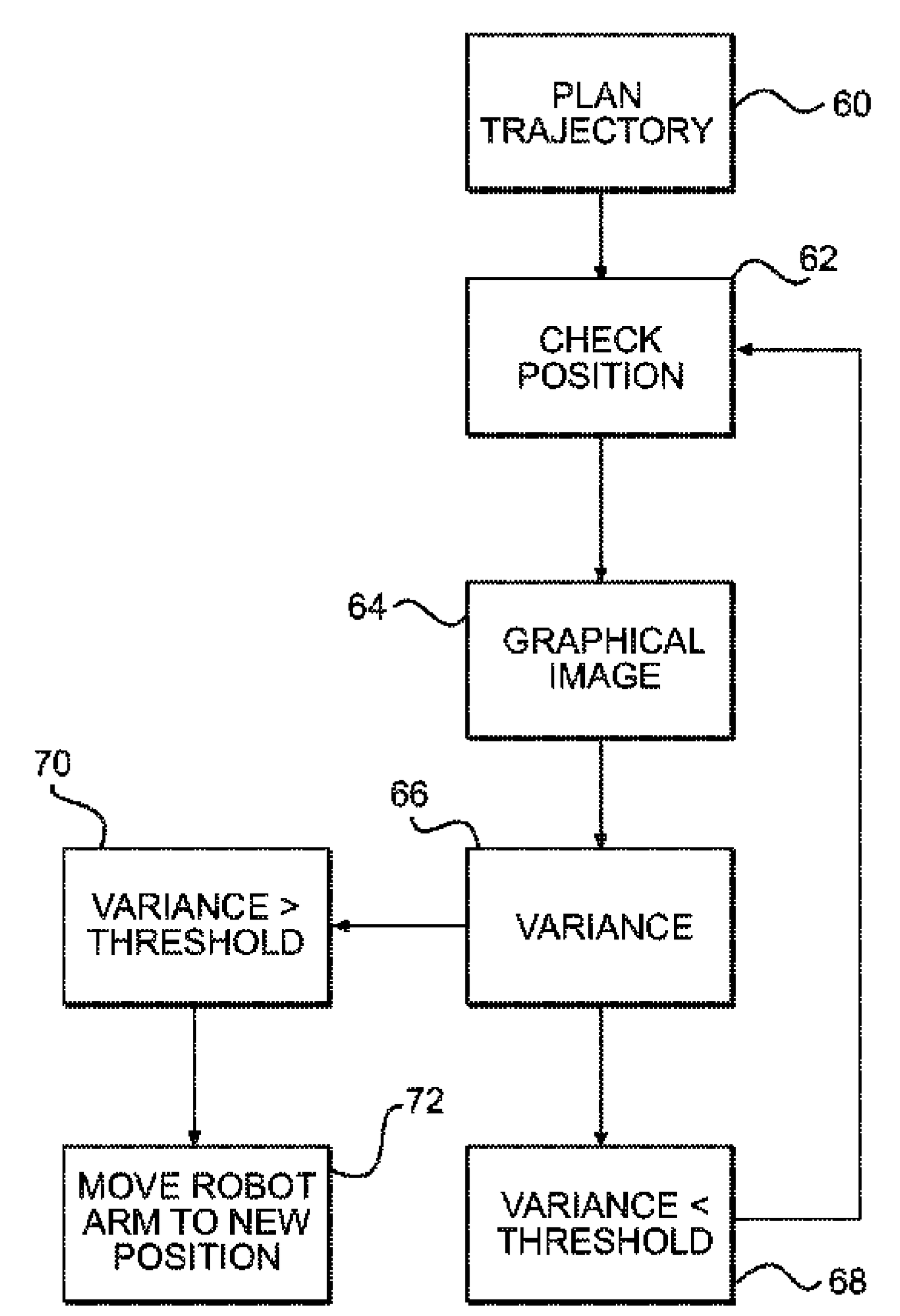
(Continued)

Primary Examiner — Sohana Tanju Khayer

(57) **ABSTRACT**

A robotic surgical system for performing surgery, the system includes a robotic arm having a force and/or torque control sensor coupled to the end-effector and configured to hold a first surgical tool. The robotic system further includes an actuator that includes controlled movement of the robotic arm and/or positioning of the end-effector. The system further includes a tracking detector having optical markers for real time detection of (i) surgical tool position and/or end-effector position and (ii) patient position. The system also includes a feedback system for moving the end effector to a planned trajectory based on the threshold distance between the planned trajectory and the actual trajectory.

17 Claims, 14 Drawing Sheets



Related U.S. Application Data

continuation of application No. 15/790,538, filed on Oct. 23, 2017, now Pat. No. 11,039,893.

(60) Provisional application No. 62/411,258, filed on Oct. 21, 2016.

(56) References Cited

U.S. PATENT DOCUMENTS

5,598,453	A	1/1997	Baba et al.
5,772,594	A	6/1998	Barrick
5,987,960	A	11/1999	Messner et al.
6,031,888	A	2/2000	Ivan et al.
6,144,875	A	11/2000	Schweikard et al.
6,203,196	B1	3/2001	Meyer et al.
6,306,126	B1	10/2001	Montezuma
6,314,311	B1	11/2001	Williams et al.
6,320,929	B1	11/2001	Von Der Haar
6,477,400	B1	11/2002	Barrick
6,484,049	B1	11/2002	Seeley et al.
6,487,267	B1	11/2002	Wolter
6,490,475	B1	12/2002	Seeley et al.
6,501,981	B1	12/2002	Schweikard et al.
6,535,756	B1	3/2003	Simon et al.
6,614,453	B1	9/2003	Suri et al.
6,614,871	B1	9/2003	Kobiki et al.
6,619,840	B2	9/2003	Rasche et al.
6,666,579	B2	12/2003	Jensen
6,757,068	B2	6/2004	Foxlin
6,782,287	B2	8/2004	Grzeszczuk et al.
6,856,826	B2	2/2005	Seeley et al.
6,856,827	B2	2/2005	Seeley et al.
6,920,347	B2	7/2005	Simon et al.
6,922,632	B2	7/2005	Foxlin
6,988,009	B2	1/2006	Grimm et al.
6,996,487	B2	2/2006	Jutras et al.
7,016,457	B1	3/2006	Senzig et al.
7,043,961	B2	5/2006	Pandey et al.
7,062,006	B1	6/2006	Pelc et al.
7,063,705	B2	6/2006	Young et al.
7,072,707	B2	7/2006	Galloway, Jr. et al.
7,099,428	B2	8/2006	Clinthorne et al.
7,108,421	B2	9/2006	Gregerson et al.
7,130,676	B2	10/2006	Barrick
7,139,418	B2	11/2006	Abovitz et al.
7,194,120	B2	3/2007	Wicker et al.
7,197,107	B2	3/2007	Arai et al.
7,231,014	B2	6/2007	Levy
7,231,063	B2	6/2007	Naimark et al.
7,301,648	B2	11/2007	Foxlin
7,313,430	B2	12/2007	Urquhart et al.
7,318,805	B2	1/2008	Schweikard et al.
7,324,623	B2	1/2008	Heuscher et al.
7,327,865	B2	2/2008	Fu et al.
7,460,637	B2	12/2008	Clinthorne et al.
7,493,153	B2	2/2009	Ahmed et al.
7,505,617	B2	3/2009	Fu et al.
7,623,902	B2	11/2009	Pacheco
7,643,862	B2	1/2010	Schoenefeld
7,661,881	B2	2/2010	Gregerson et al.
7,683,331	B2	3/2010	Chang
7,683,332	B2	3/2010	Chang
7,702,379	B2	4/2010	Avinash et al.
7,702,477	B2	4/2010	Tuemmler et al.
7,711,083	B2	5/2010	Heigl et al.
7,725,253	B2	5/2010	Foxlin
7,726,171	B2	6/2010	Langlotz et al.
7,760,849	B2	7/2010	Zhang
7,796,728	B2	9/2010	Bergfjord
7,813,838	B2	10/2010	Sommer
7,835,778	B2	11/2010	Foley et al.
7,835,784	B2	11/2010	Mire et al.
7,840,256	B2	11/2010	Lakin et al.
7,844,320	B2	11/2010	Shahidi
7,853,305	B2	12/2010	Simon et al.
7,853,313	B2	12/2010	Thompson
7,900,524	B2	3/2011	Calloway et al.
7,940,999	B2	5/2011	Liao et al.
7,945,012	B2	5/2011	Ye et al.
7,945,021	B2	5/2011	Shapiro et al.
8,019,045	B2	9/2011	Kato
8,021,310	B2	9/2011	Sanborn et al.
8,052,688	B2	11/2011	Wolf, II
8,086,299	B2	12/2011	Adler et al.
8,098,914	B2	1/2012	Liao et al.
8,100,950	B2	1/2012	St. Clair et al.
8,116,430	B1	2/2012	Shapiro et al.
8,121,249	B2	2/2012	Wang et al.
8,150,494	B2	4/2012	Simon et al.
8,208,708	B2	6/2012	Homan et al.
8,224,024	B2	7/2012	Foxlin et al.
8,311,611	B2	11/2012	Csavoy et al.
8,335,557	B2	12/2012	Maschke
8,358,818	B2	1/2013	Miga et al.
8,379,791	B2	2/2013	Forthmann et al.
8,386,019	B2	2/2013	Camus et al.
8,394,099	B2	3/2013	Patwardhan
8,462,911	B2	6/2013	Vesel et al.
8,526,700	B2	9/2013	Isaacs
8,541,970	B2	9/2013	Nowlin et al.
8,560,118	B2	10/2013	Green et al.
8,597,198	B2	12/2013	Sanborn et al.
8,611,985	B2	12/2013	Lavallee et al.
8,630,389	B2	1/2014	Kato
8,634,897	B2	1/2014	Simon et al.
8,660,635	B2	2/2014	Simon et al.
8,678,647	B2	3/2014	Gregerson et al.
8,696,458	B2	4/2014	Foxlin et al.
8,706,185	B2	4/2014	Foley et al.
8,727,618	B2	5/2014	Maschke et al.
8,738,115	B2	5/2014	Amberg et al.
8,740,882	B2	6/2014	Jun et al.
8,781,186	B2	7/2014	Clements et al.
8,781,630	B2	7/2014	Banks et al.
8,787,520	B2	7/2014	Baba
8,792,704	B2	7/2014	Isaacs
8,798,231	B2	8/2014	Notohara et al.
8,812,077	B2	8/2014	Dempsey
8,814,793	B2	8/2014	Brabrand
8,818,105	B2	8/2014	Myronenko et al.
8,821,511	B2	9/2014	Von Jako et al.
8,867,703	B2	10/2014	Shapiro et al.
8,888,821	B2	11/2014	Rezach et al.
8,964,934	B2	2/2015	Ein-Gal
8,992,580	B2	3/2015	Bar et al.
8,996,169	B2	3/2015	Lightcap et al.
9,001,963	B2	4/2015	Sowards-Emmerd et al.
9,002,076	B2	4/2015	Khadem et al.
9,044,190	B2	6/2015	Rubner et al.
9,107,683	B2	8/2015	Hourtash et al.
9,125,556	B2	9/2015	Zehavi et al.
9,131,986	B2	9/2015	Greer et al.
9,215,968	B2	12/2015	Schostek et al.
9,308,050	B2	4/2016	Kostrzewski et al.
9,380,984	B2	7/2016	Li et al.
9,393,039	B2	7/2016	Lechner et al.
9,398,886	B2	7/2016	Gregerson et al.
9,398,890	B2	7/2016	Dong et al.
9,414,859	B2	8/2016	Ballard et al.
9,420,975	B2	8/2016	Gutfleisch et al.
9,492,235	B2	11/2016	Hourtash et al.
9,592,096	B2	3/2017	Maillet et al.
9,750,465	B2	9/2017	Engel et al.
9,757,203	B2	9/2017	Hourtash et al.
9,795,354	B2	10/2017	Menegaz et al.
9,814,535	B2	11/2017	Bar et al.
9,820,783	B2	11/2017	Donner et al.
9,833,265	B2	11/2017	Donner et al.
9,848,922	B2	12/2017	Tohmeh et al.
9,925,011	B2	3/2018	Gombert et al.
9,931,025	B1	4/2018	Graetzel et al.
10,034,717	B2	7/2018	Miller et al.
2001/0036302	A1	11/2001	Miller
2004/0016077	A1*	1/2004	Song G05D 1/0246 15/340.1

(56) **References Cited**

U.S. PATENT DOCUMENTS

2004/0076259	A1	4/2004	Jensen et al.	
2006/0184396	A1	8/2006	Dennis et al.	
2006/0247517	A1*	11/2006	Labadie	A61B 90/39 600/426
2006/0291612	A1	12/2006	Nishide et al.	
2007/0038059	A1	2/2007	Sheffer et al.	
2007/0073133	A1	3/2007	Schoenefeld	
2008/0004523	A1	1/2008	Jensen	
2008/0013809	A1	1/2008	Zhu et al.	
2008/0082109	A1	4/2008	Moll et al.	
2008/0108991	A1	5/2008	Von Jako	
2008/0144906	A1	6/2008	Allred et al.	
2008/0161680	A1	7/2008	Von Jako et al.	
2008/0235052	A1	9/2008	Node-Langlois et al.	
2008/0269596	A1	10/2008	Revie et al.	
2008/0287781	A1	11/2008	Revie et al.	
2008/0300477	A1	12/2008	Lloyd et al.	
2008/0302950	A1	12/2008	Park et al.	
2008/0306490	A1	12/2008	Lakin et al.	
2008/0319311	A1	12/2008	Hamadeh	
2009/0185655	A1	7/2009	Koken et al.	
2009/0198121	A1	8/2009	Hoheisel	
2010/0022874	A1	1/2010	Wang et al.	
2010/0039506	A1	2/2010	Sarvestani et al.	
2010/0125286	A1	5/2010	Wang et al.	
2010/0228117	A1	9/2010	Hartmann	
2010/0274120	A1	10/2010	Heuscher	
2011/0098553	A1	4/2011	Robbins et al.	
2011/0282189	A1	11/2011	Graumann	
2011/0286573	A1	11/2011	Schretter et al.	
2012/0035507	A1	2/2012	George et al.	
2012/0051498	A1	3/2012	Koishi	
2012/0143084	A1	6/2012	Shoham	
2012/0226145	A1	9/2012	Chang et al.	
2012/0235909	A1	9/2012	Birkenbach et al.	
2012/0294498	A1	11/2012	Popovic	
2013/0016889	A1	1/2013	Myronenko et al.	
2013/0060146	A1	3/2013	Yang et al.	
2013/0094742	A1	4/2013	Feilkas	
2013/0113791	A1	5/2013	Isaacs et al.	
2013/0165937	A1	6/2013	Patwardhan	
2013/0281821	A1	10/2013	Liu et al.	
2013/0307955	A1	11/2013	Deitz et al.	
2013/0342578	A1	12/2013	Isaacs	
2013/0345757	A1	12/2013	Stad	
2014/0046132	A1	2/2014	Hoeg et al.	
2014/0049629	A1	2/2014	Siewerdsen et al.	
2014/0080086	A1	3/2014	Chen	
2014/0096369	A1	4/2014	Matsumoto et al.	
2014/0121676	A1	5/2014	Kostrzewski et al.	
2014/0135796	A1	5/2014	Simon et al.	
2014/0130810	A1	8/2014	Azizian et al.	
2014/0221819	A1	8/2014	Sarment	
2014/0234804	A1	8/2014	Huang et al.	
2014/0275981	A1*	9/2014	Selover	A61B 5/061 600/424
2014/0371577	A1	12/2014	Maillet et al.	
2015/0039034	A1	2/2015	Frankel et al.	
2015/0085970	A1	3/2015	Bouhnik et al.	
2015/0100066	A1*	4/2015	Kostrzewski	A61B 34/30 606/130
2015/0146847	A1	5/2015	Liu	
2015/0150524	A1	6/2015	Yorkston et al.	
2015/0182285	A1*	7/2015	Yen	A61B 17/1626 606/86 R
2015/0196261	A1	7/2015	Funk	
2015/0213633	A1	7/2015	Chang et al.	
2015/0335480	A1	11/2015	Alvarez et al.	
2015/0342647	A1	12/2015	Frankel et al.	
2016/0005194	A1	1/2016	Schretter et al.	
2016/0166329	A1	6/2016	Langan et al.	
2016/0235480	A1	8/2016	Scholl et al.	
2016/0249990	A1	9/2016	Glozman et al.	
2016/0302871	A1	10/2016	Gregerson et al.	
2016/0320322	A1	11/2016	Suzuki	
2016/0331335	A1	11/2016	Gregerson et al.	
2017/0135770	A1	5/2017	Scholl et al.	
2017/0143284	A1	5/2017	Sehnert et al.	
2017/0143426	A1	5/2017	Isaacs et al.	
2017/0156816	A1	6/2017	Ibrahim	
2017/0165837	A1*	6/2017	Asano	A61B 34/30
2017/0202629	A1	7/2017	Maillet et al.	
2017/0212723	A1	7/2017	Atarot et al.	
2017/0215825	A1	8/2017	Johnson et al.	
2017/0215826	A1	8/2017	Johnson et al.	
2017/0215827	A1	8/2017	Johnson et al.	
2017/0231710	A1	8/2017	Scholl et al.	
2017/0258426	A1	9/2017	Risher-Kelly et al.	
2017/0273748	A1	9/2017	Hourtash et al.	
2017/0296277	A1	10/2017	Hourtash et al.	
2017/0360493	A1	12/2017	Zucher et al.	

* cited by examiner

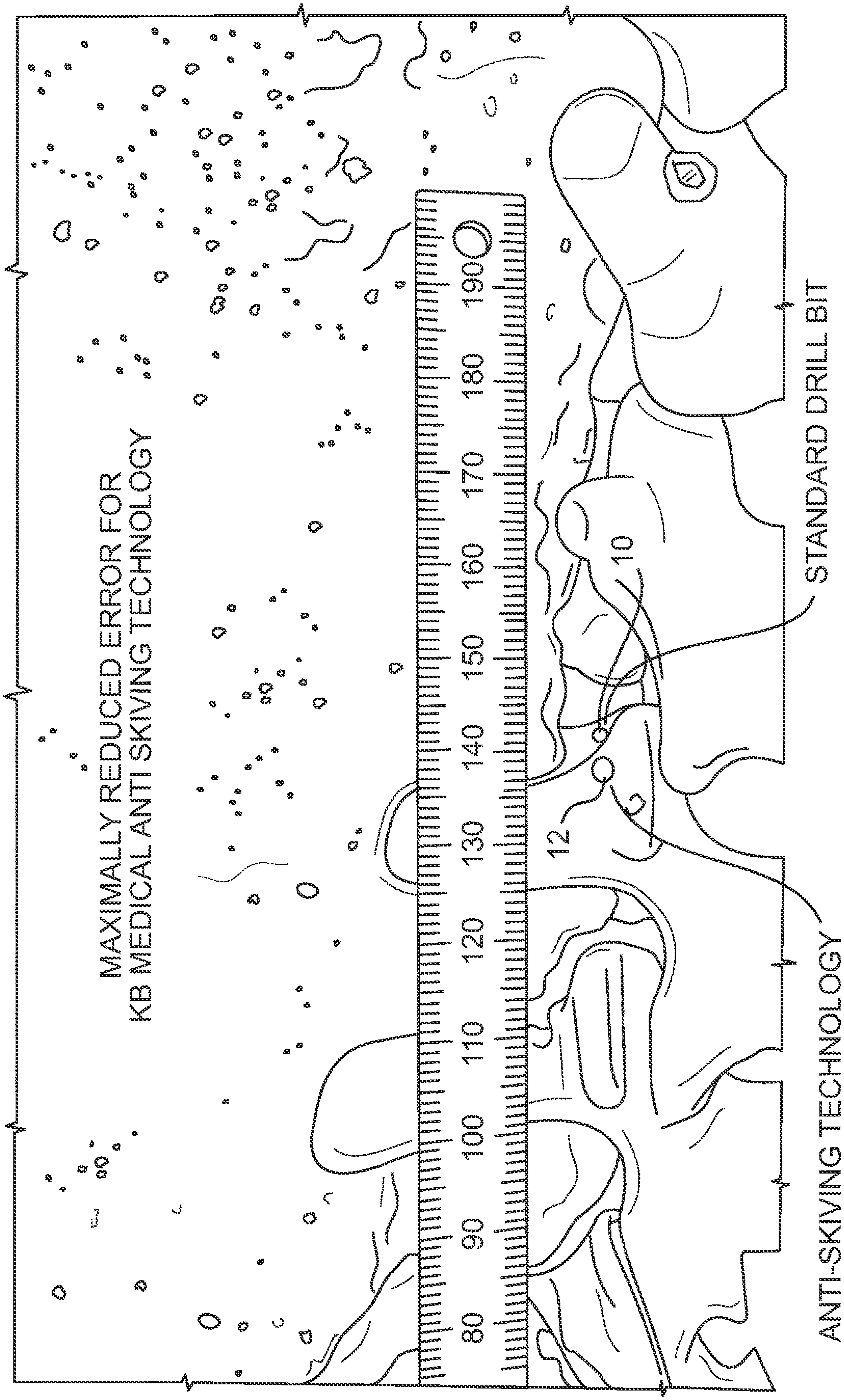
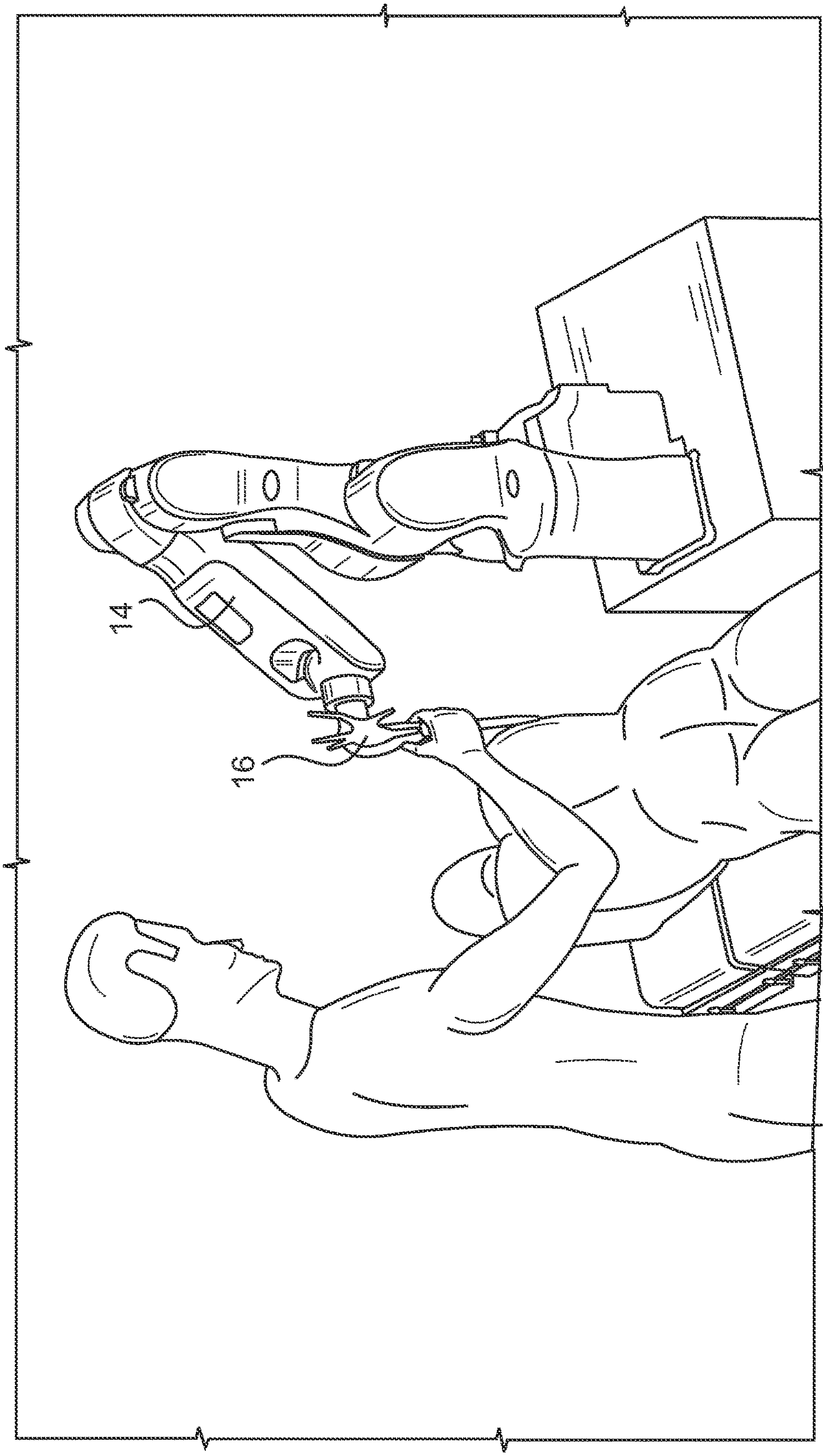
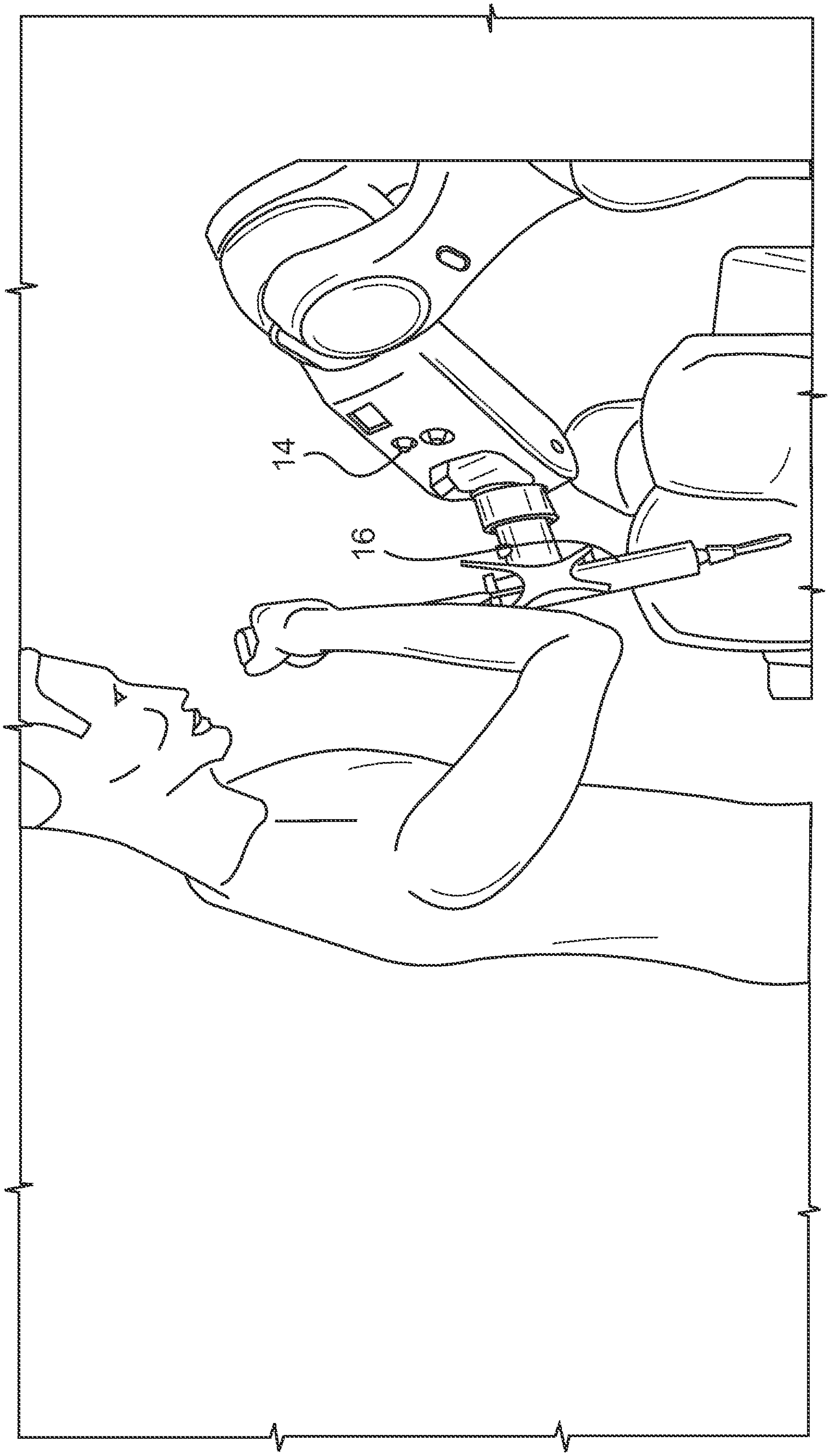

MAXIMALLY REDUCED ERROR FOR
KB MEDICAL ANTI SKIVING TECHNOLOGY
80
90
100
110
120
130
140
150
160
170
180
190
10
12
STANDARD DRILL BIT
ANTI-SKIVING TECHNOLOGY

FIG. 1



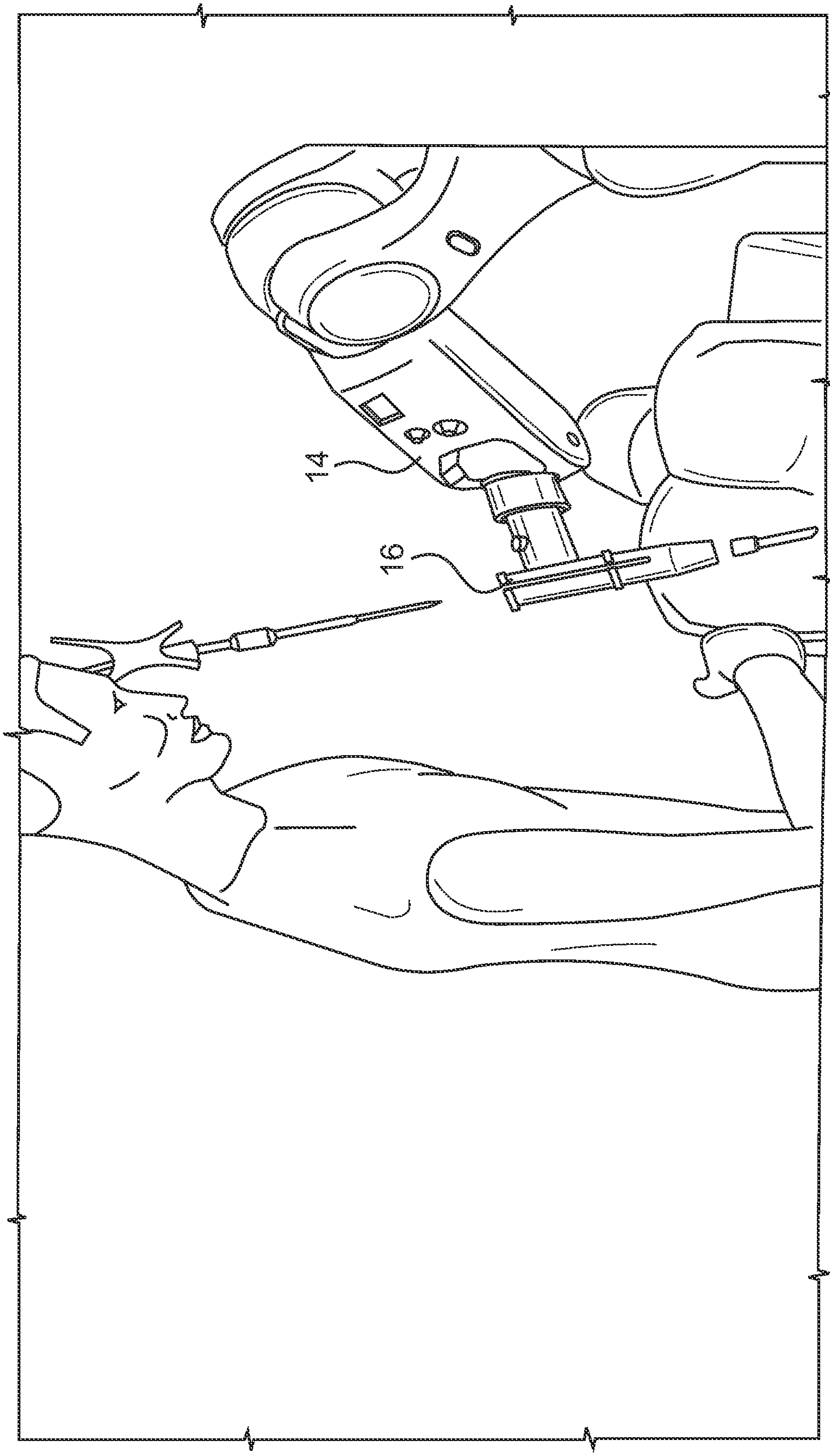
SURGEON IS GUIDED BY THE ROBOT
THE QUICKLY FIND THE TRAJECTORY
(R) - SLOW DOWN

FIG. 2A



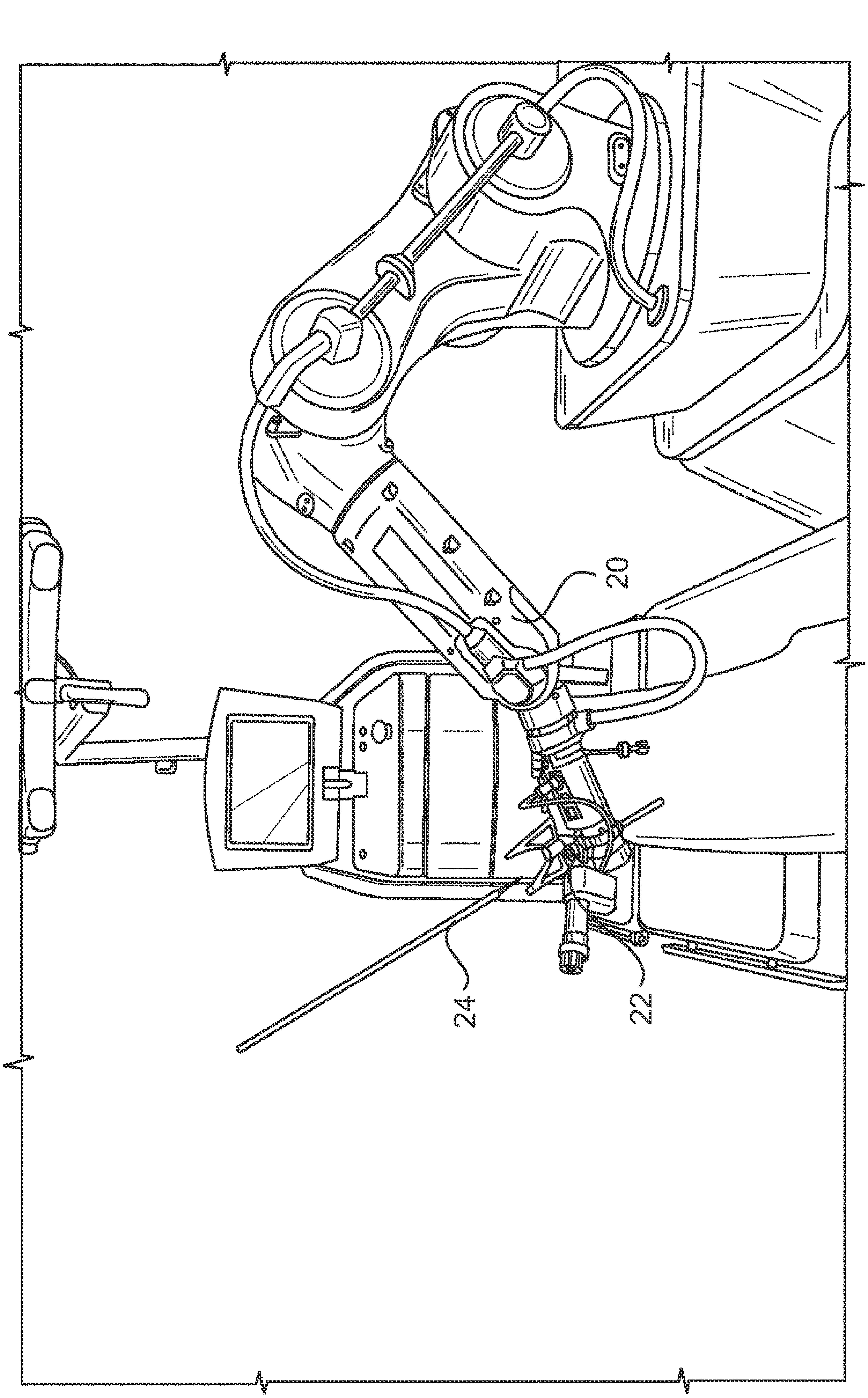
TRAJECTORIES CAN BE OBTAINED FROM NAVIGATION,
MANUAL OR AUTOMATIC PLANNING

FIG. 2B



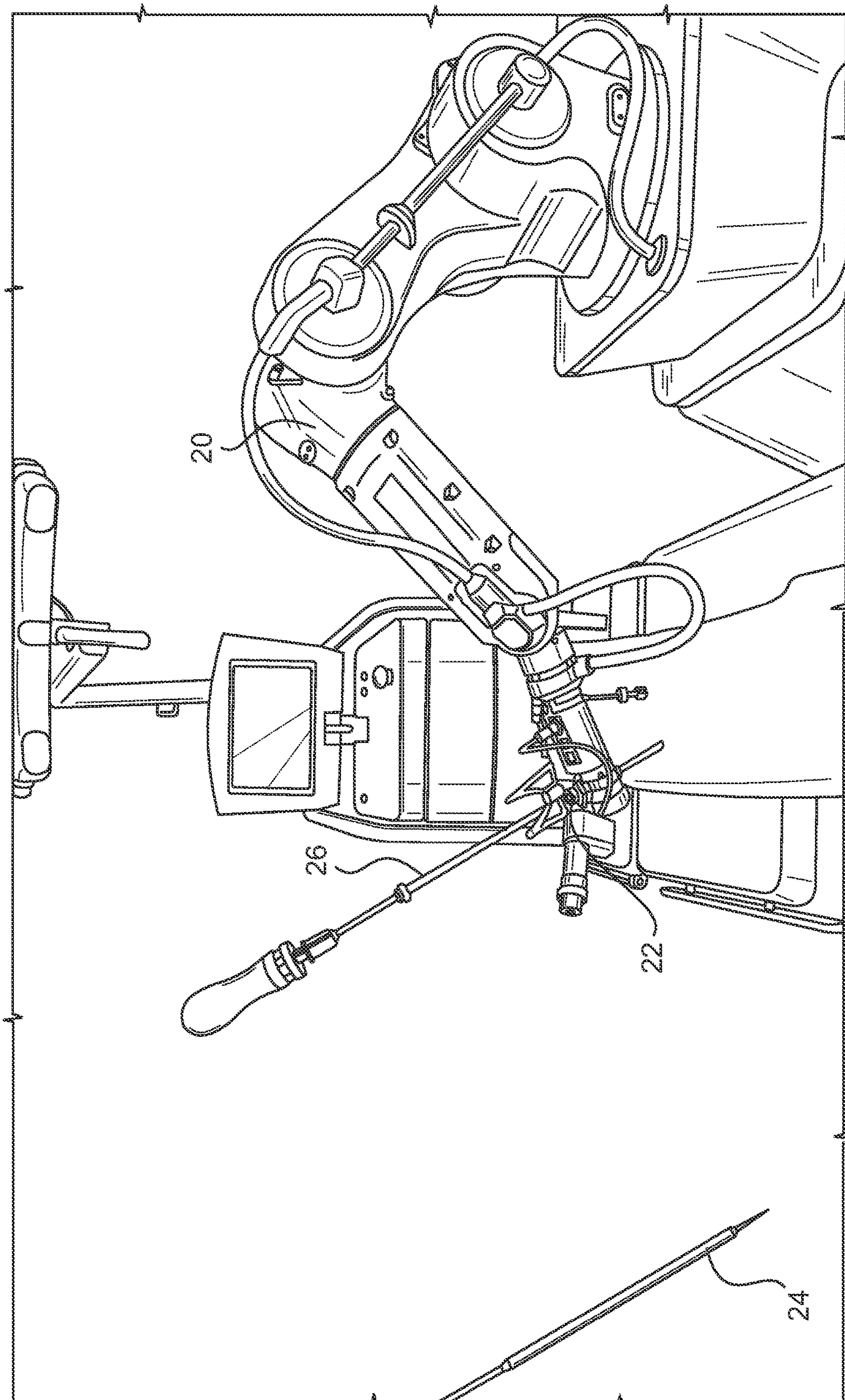
SURGEON CAN FINE TUNE TRAJECTORY
USING ROBOT HAPTIC CONTROL

FIG. 2C



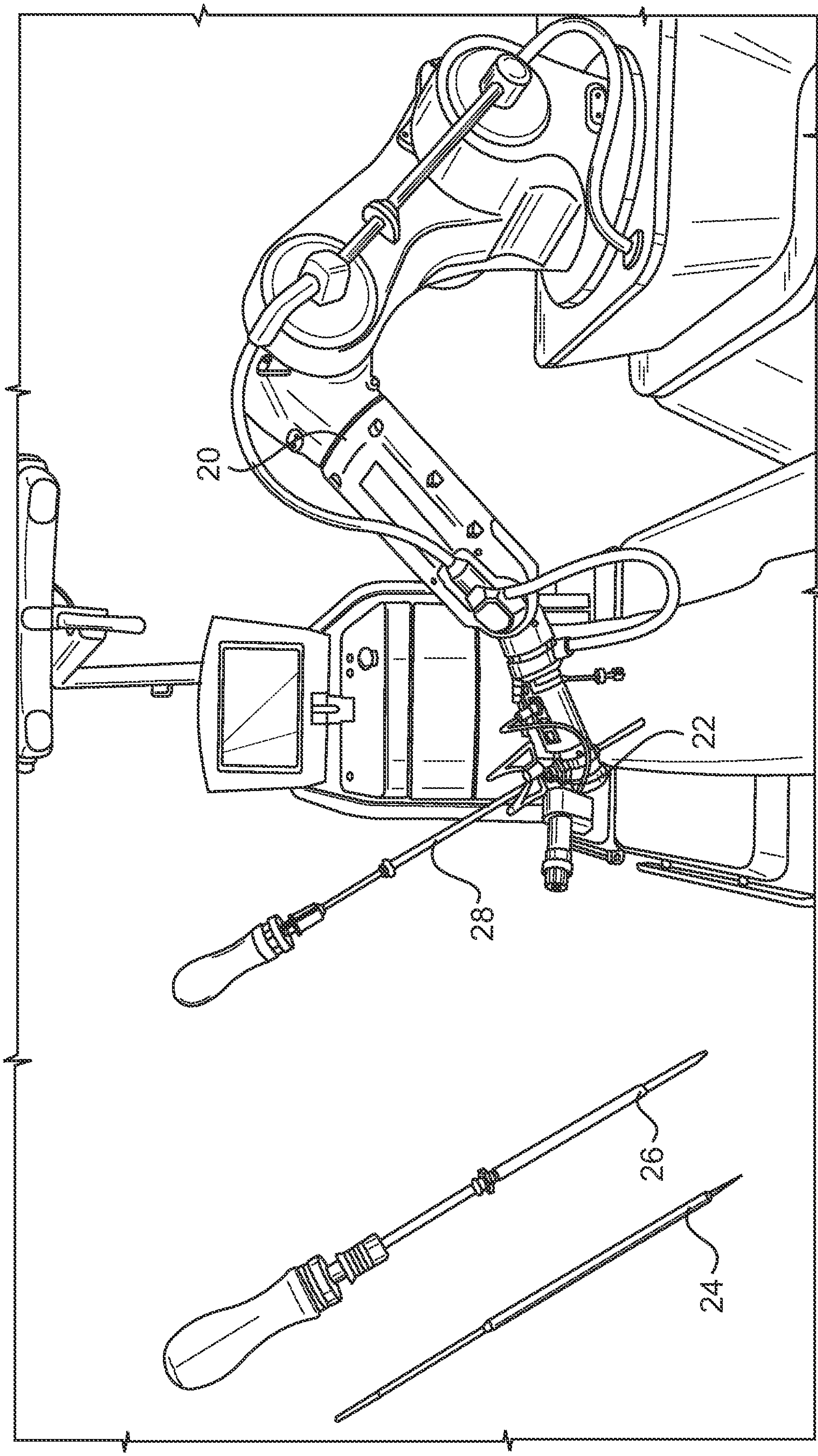
STEP 1: DRILL

FIG. 3A



TAP ENTERS INTO PREPARED HOLE

FIG. 3B



STEP 3: PLACE SCREW

FIG. 3C

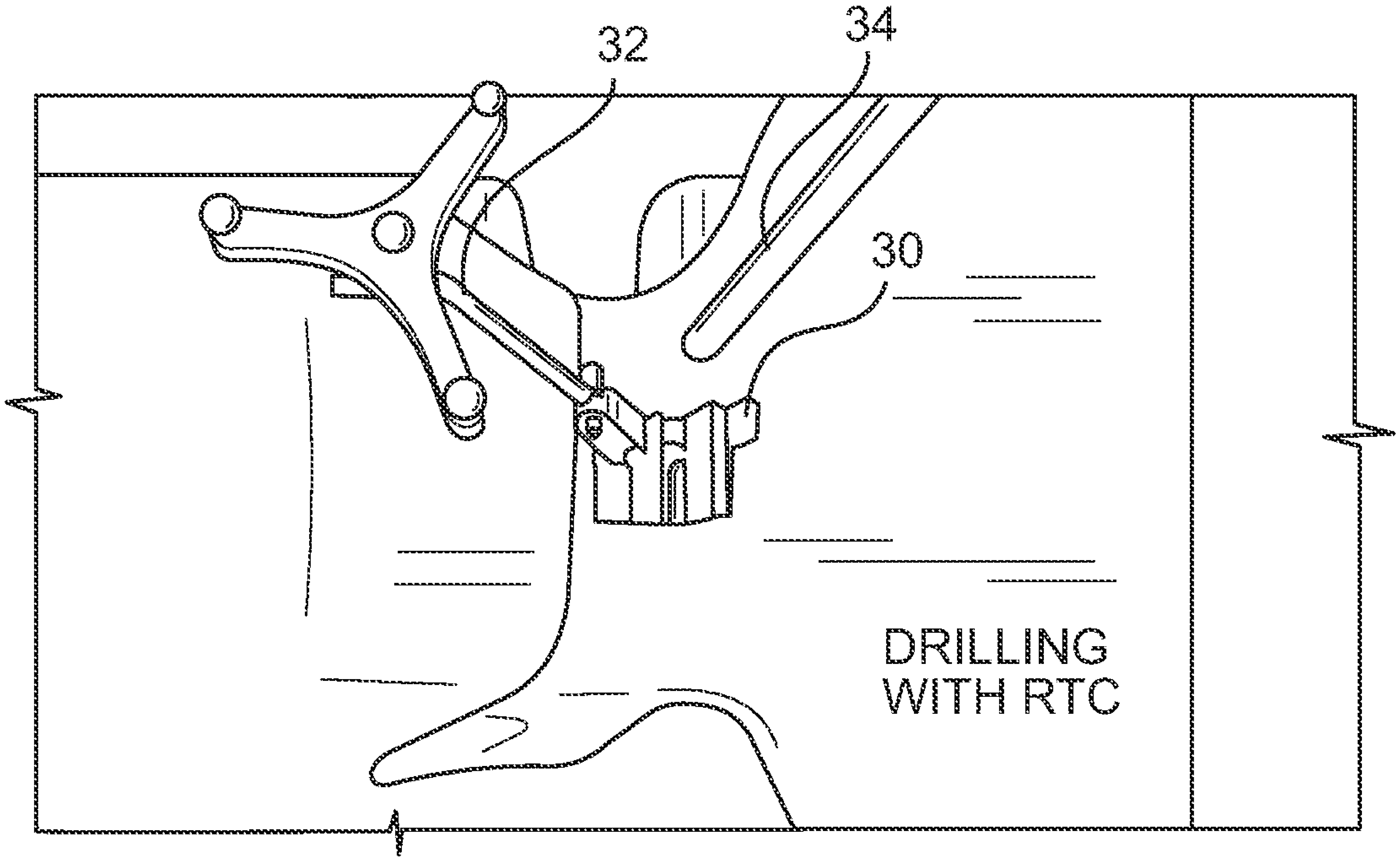


FIG. 4A

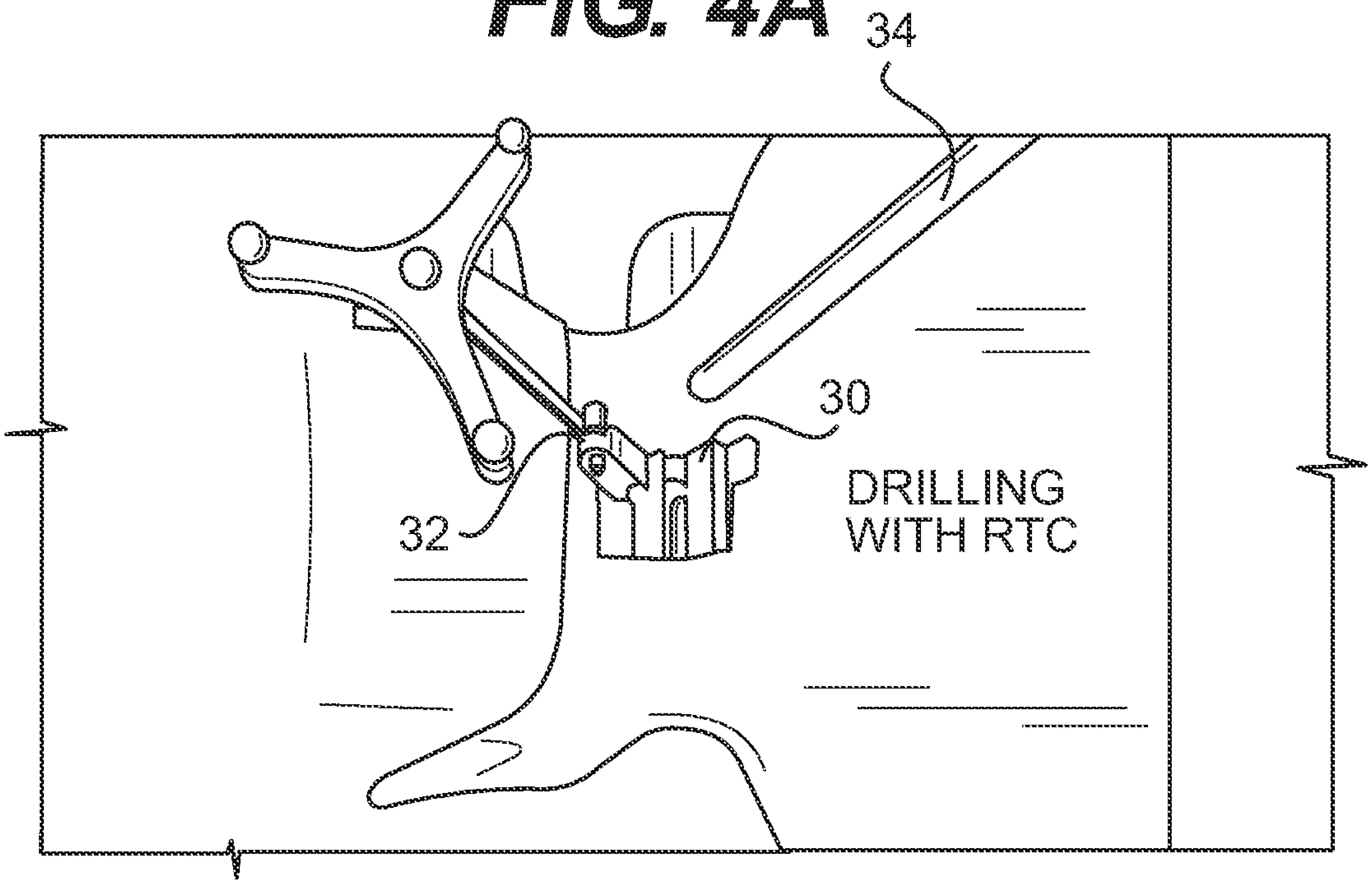
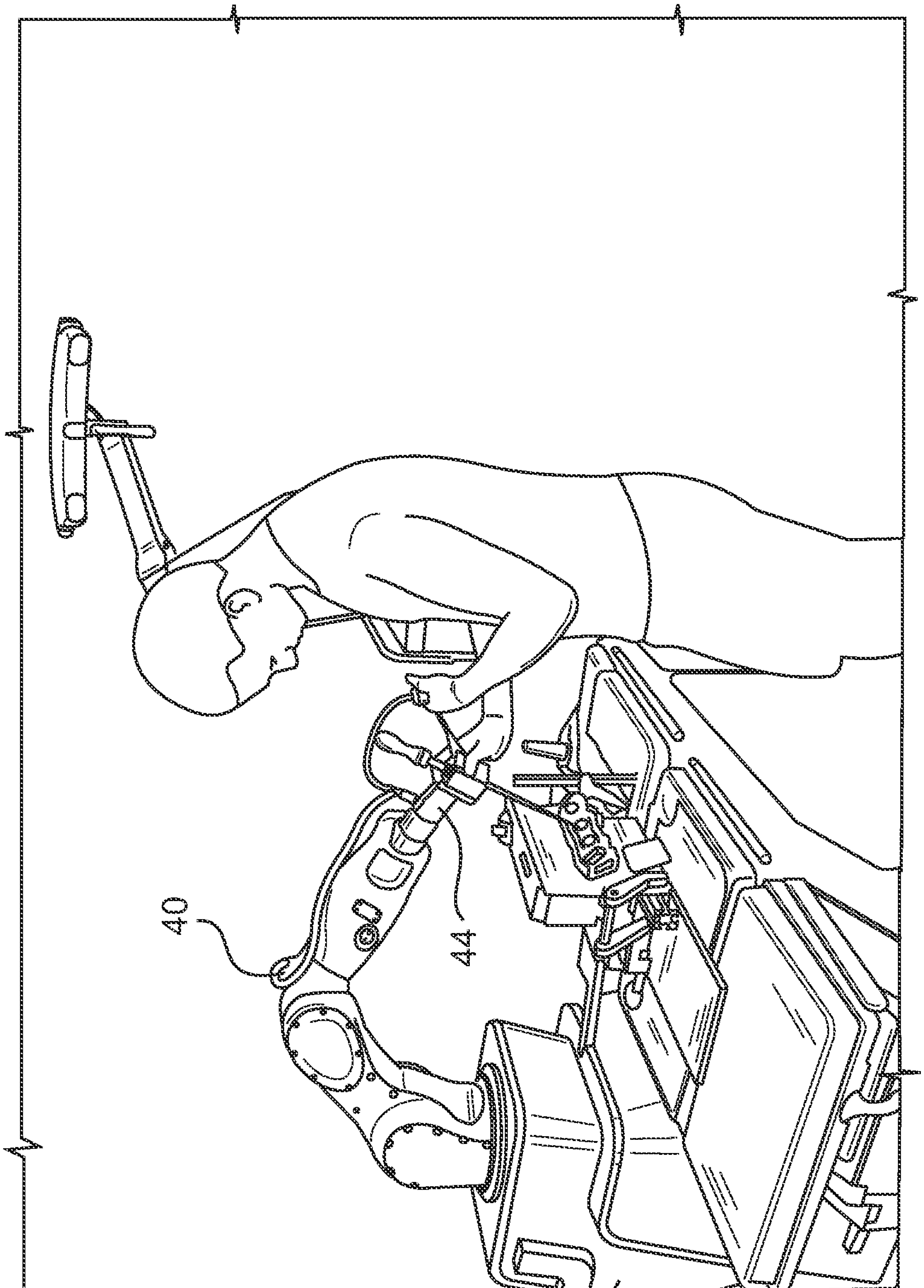
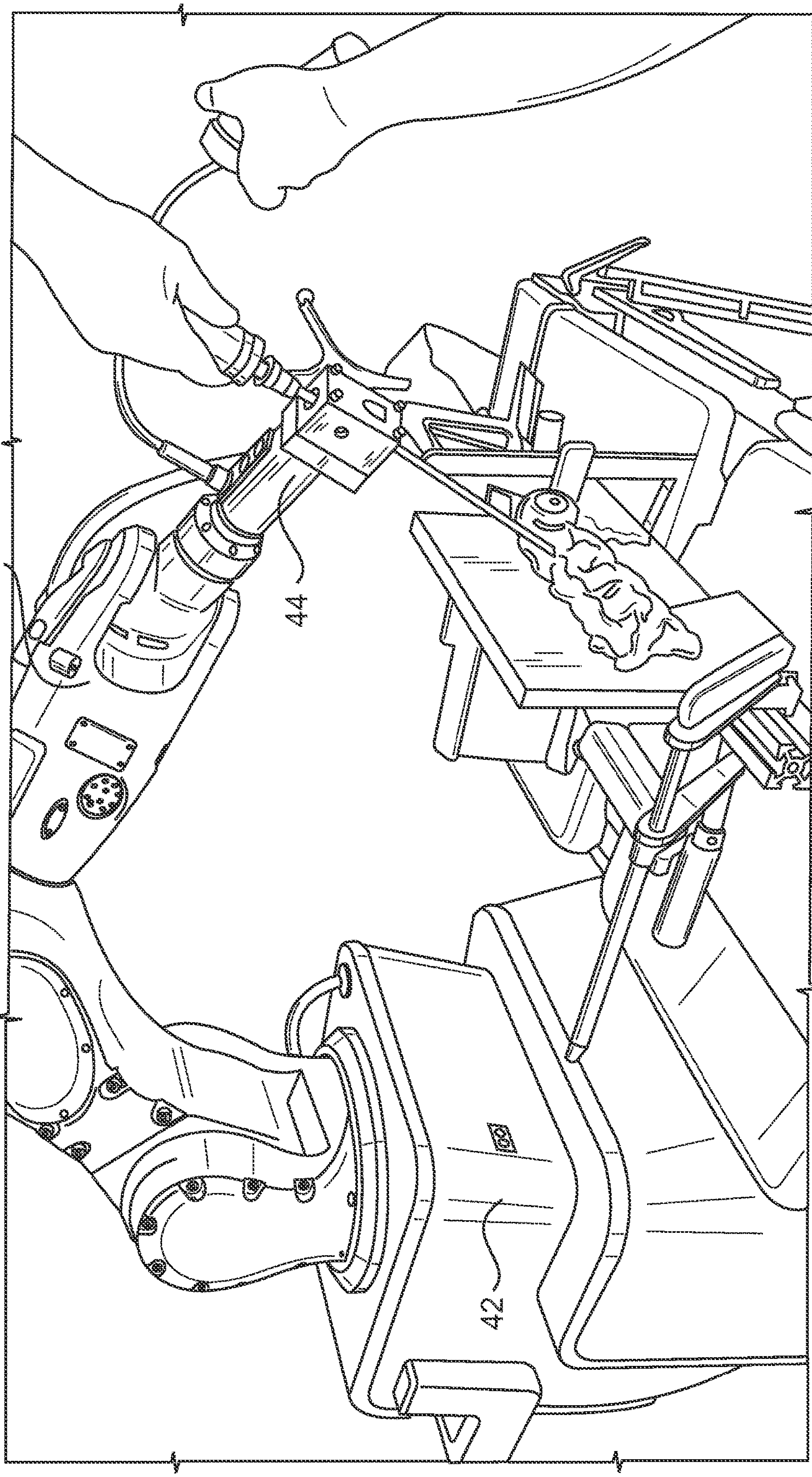


FIG. 4B



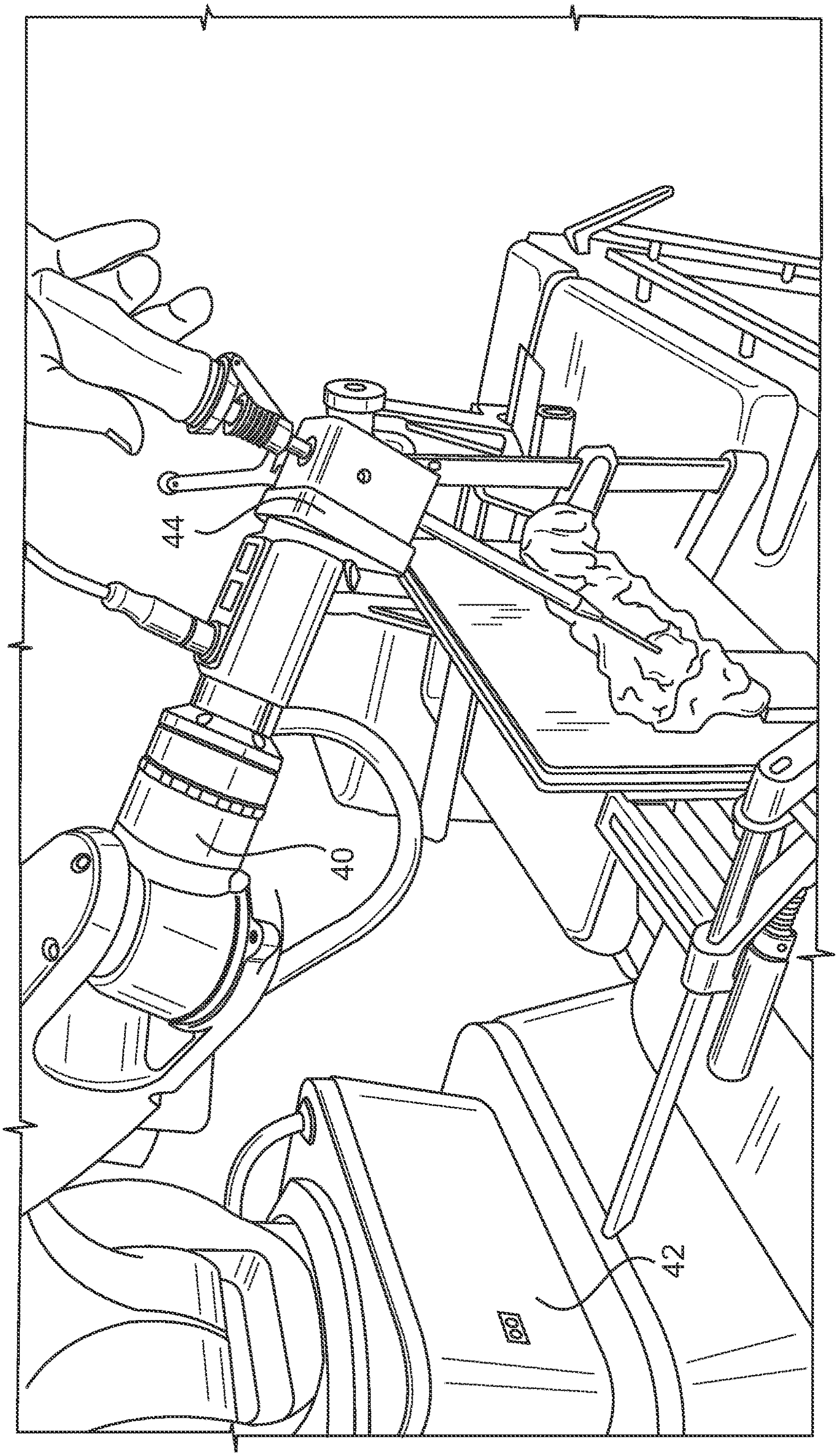
PLAN TRAJECTORY

FIG. 5A



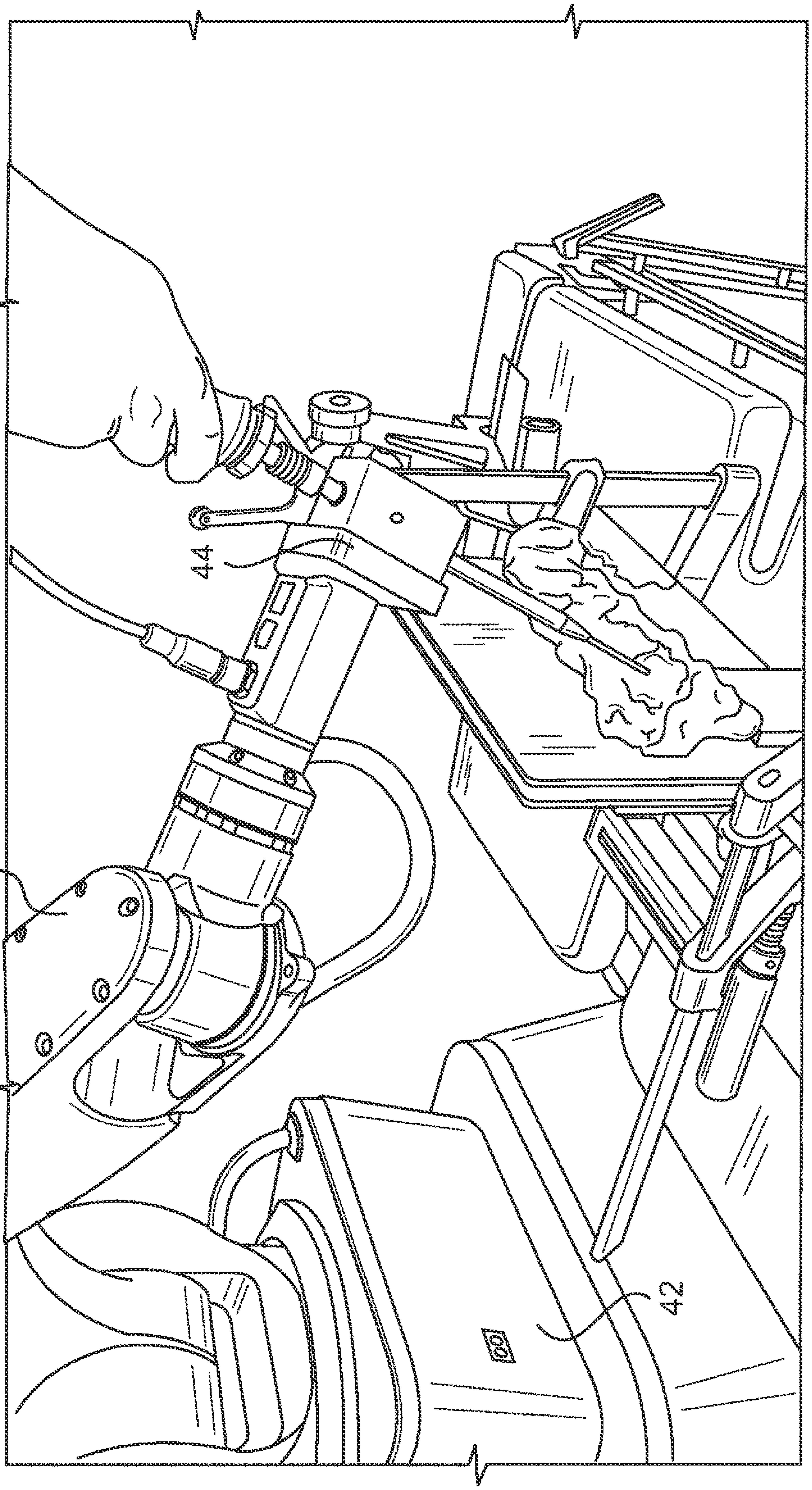
PUNCH CORTICAL BONE WITH AN AWL
(OPTONAL)

FIG. 5B



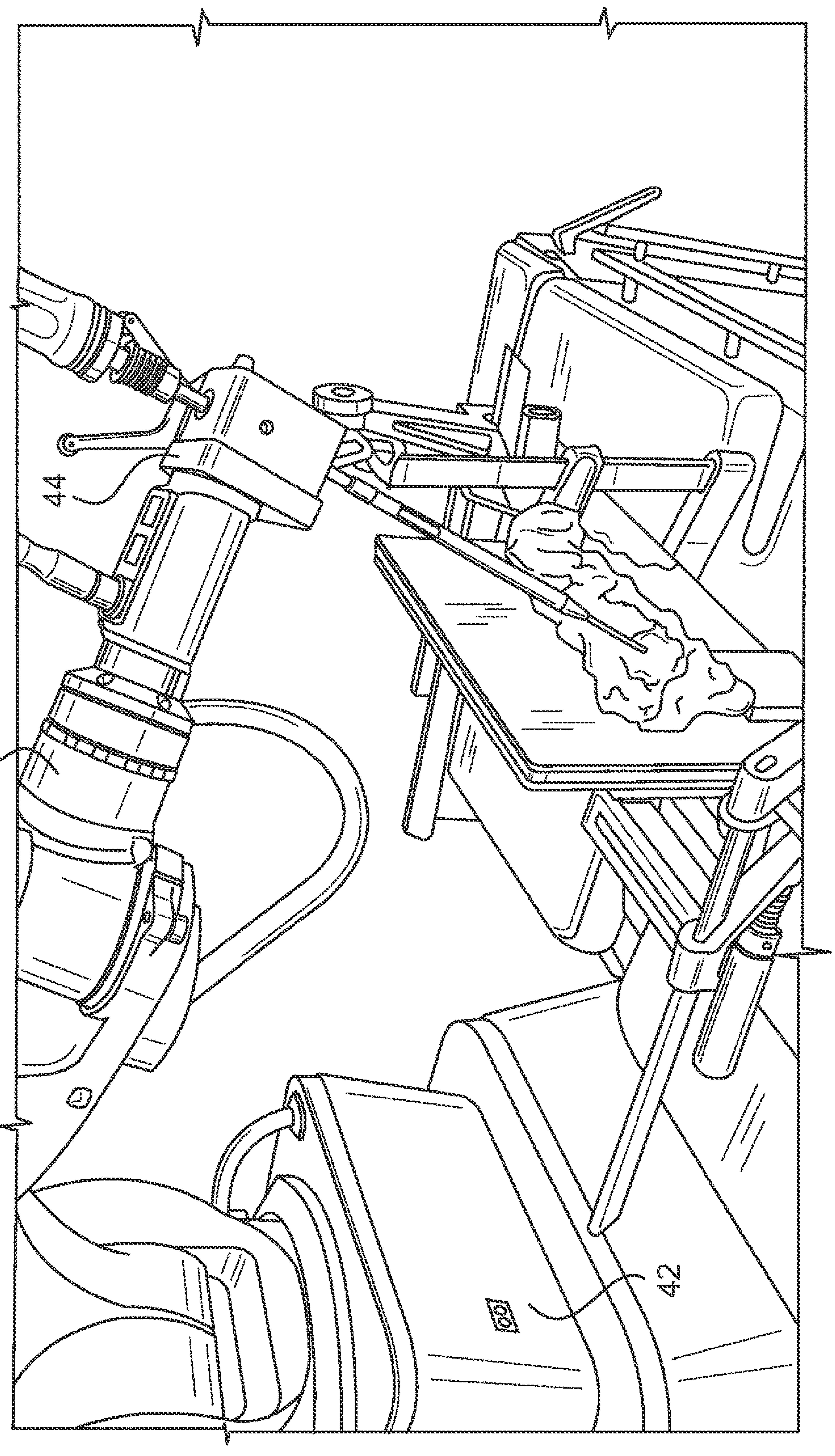
MAKE HOLE AND TAP

FIG. 5C



ROBOT TRAJECTORY-LOCK MODE
FOLLOWS ADVANCEMENT OF AN INSTRUMENT

FIG. 5D



SREW PLACEMENT IN THE PREPARED HOLE

FIG. 5E

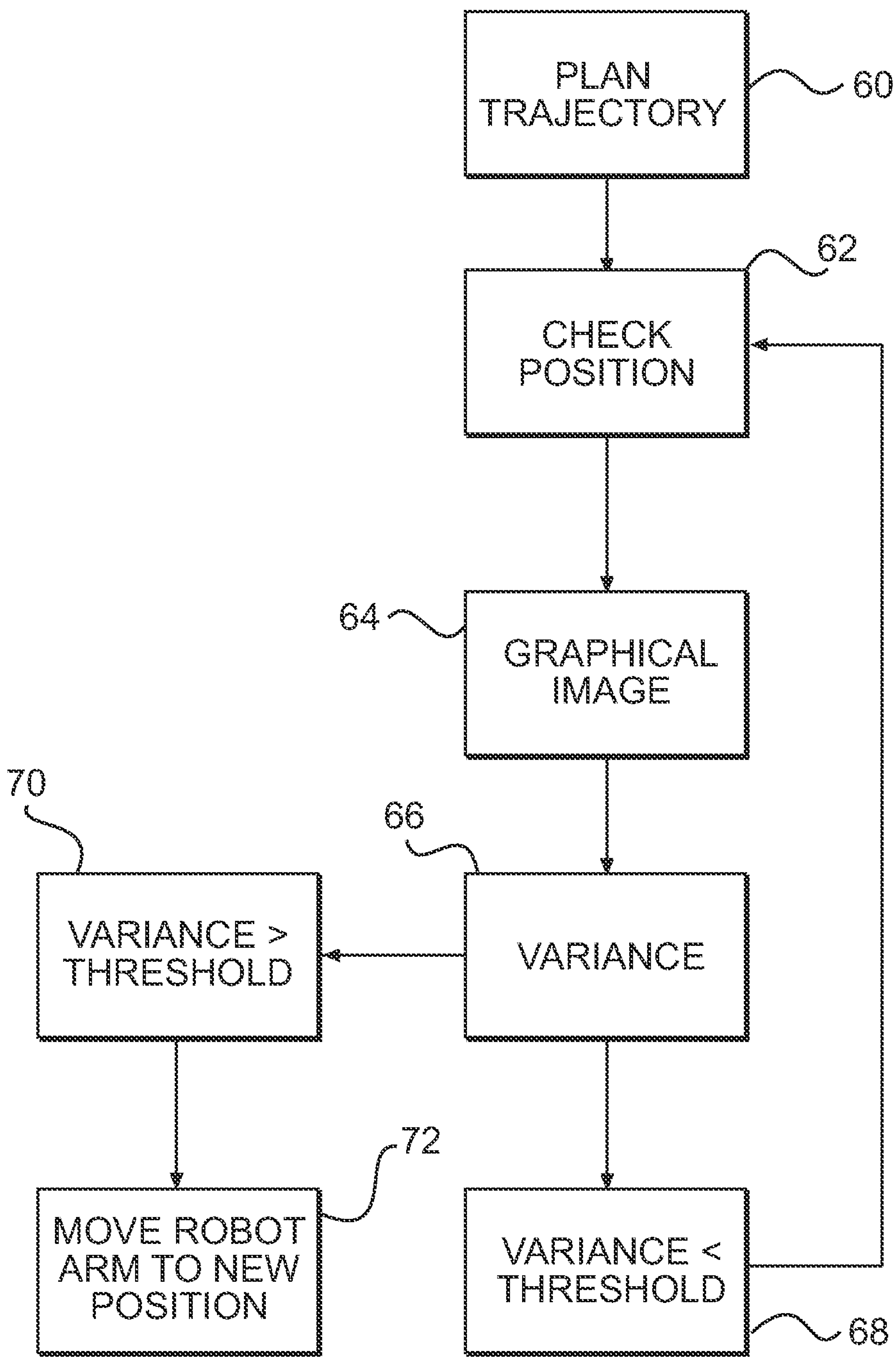

PLAN TRAJECTORY
60
62
CHECK POSITION
64
GRAPHICAL IMAGE
70
66
VARIANCE > THRESHOLD
VARIANCE
72
MOVE ROBOT ARM TO NEW POSITION
VARIANCE < THRESHOLD
68

FIG. 6

ROBOTIC SURGICAL SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of U.S. application Ser. No. 17/352,505, filed on Jun. 21, 2021 (published as U.S. Pat. Pub. No. 2021-0307848), which is a continuation of U.S. application Ser. No. 15/790,538, filed on Oct. 23, 2017, now U.S. Pat. No. 11,039,893, which claims priority to U.S. provisional application Ser. No. 62/411,258, filed on Oct. 21, 2016, all of which are incorporated herein by reference in their entireties for all purposes.

BACKGROUND

Robotic-assisted surgical systems have been developed to improve surgical precision and enable the implementation of new surgical procedures. For example, robotic systems have been developed to sense a surgeon's hand movements and translate them to scaled-down micro-movements and filter out unintentional tremors for precise microsurgical techniques in organ transplants, reconstructions, and minimally invasive surgeries. Feedback-controlled robotic systems have also been developed to provide smoother manipulation of a surgical tool during a procedure than could be achieved by an unaided surgeon.

However, widespread acceptance of robotic systems by surgeons and hospitals is limited for a variety of reasons. Current systems are expensive to own and maintain. They often require extensive preoperative surgical planning prior to use, and they extend the required preparation time in the operating room. They are physically intrusive, possibly obscuring portions of a surgeon's field of view and blocking certain areas around the operating table, such that a surgeon and/or surgical assistants are relegated to one side of the operating table. Current systems may also be non-intuitive or otherwise cumbersome to use, particularly for surgeons who have developed a special skill or "feel" for performing certain maneuvers during surgery and who find that such skill cannot be implemented using the robotic system. Finally, robotic surgical systems may be vulnerable to malfunction or operator error, despite safety interlocks and power backups.

Spinal surgeries often require precision drilling and placement of screws or other implements in relation to the spine, and there may be constrained access to the vertebrae during surgery that makes such maneuvers difficult. Catastrophic damage or death may result from improper drilling or maneuvering of the body during spinal surgery, due to the proximity of the spinal cord and arteries. Common spinal surgical procedures include a discectomy for removal of all or part of a disk, a foraminotomy for widening of the opening where nerve roots leave the spinal column, a laminectomy for removal of the lamina or bone spurs in the back, and spinal fusion for fusing of two vertebrae or vertebral segments together to eliminate pain caused by movement of the vertebrae.

Spinal surgeries that involve screw placement require preparation of holes in bone (e.g., vertebral segments) prior to placement of the screws. Where such procedures are performed manually, in some implementations, a surgeon judges a drill trajectory for subsequent screw placement on the basis of pre-operative CT scans. Other manual methods which do not involve usage of the pre-operative CT scans, such as fluoroscopy, 3D fluoroscopy or natural landmark-based, may be used to determine the trajectory for preparing

holes in bone prior to placement of the screws. In some implementations, the surgeon holds the drill in his hand while drilling, and fluoroscopic images are obtained to verify if the trajectory is correct. Some surgical techniques involve usage of different tools, such as a pedicle finder or K-wires. Such procedures rely strongly on the expertise of the surgeon, and there is significant variation in success rate among different surgeons. Screw misplacement is a common problem in such surgical procedures.

Image-guided spinal surgeries involve optical tracking to aid in screw placement. However, such procedures are currently performed manually, and surgical tools can be inaccurately positioned despite virtual tracking. A surgeon is required to coordinate his real-world, manual manipulation of surgical tools using images displayed on a two dimensional screen. Such procedures can be non-intuitive and require training, since the surgeon's eye must constantly scan both the surgical site and the screen to confirm alignment. Furthermore, procedural error can result in registration inaccuracy of the image-guiding system, rendering it useless, or even misleading. Thus, there is a need for a system for stabilizing surgical instruments while allowing the instruments and the instrument holder to be both easily sterilized and installed and removed from the robotic system without deteriorating localization precision as well as attachment rigidity.

SUMMARY OF THE INVENTION

In an exemplary embodiment, a robotic surgical system includes a robotic arm comprising a force and/or torque control end-effector configured to hold a first surgical tool; an actuator for controlled movement of the robotic arm and/or positioning of the end-effector; a tracking detector for real time detection of surgical tool position and/or end-effector position and patient position; and a processor and a non-transitory computer readable medium storing instructions thereon wherein the instructions, when executed, cause the processor to: access or generate a virtual representation of a patient situation; obtain a real-time surgical tool position and/or end-effector position and patient position from the tracking detector; and maintain a surgical instrument along a pre-planned trajectory that is stored in the non-transitory computer readable medium.

In another exemplary embodiment, the instructions, when executed, cause the processor to: determine the instrument is within a threshold distance of the pre-planned trajectory; and move the robotic arm such that the instrument is appropriately aligned with the trajectory.

In another exemplary embodiment, the threshold distance is greater than zero (e.g., greater than 0.1 cm, 0.5 cm, or 1 cm) and less than 1 meter (e.g., less than 20 cm, 10 cm, 5 cm, 3 cm).

In other embodiments, the surgical robotic system may be used with pre-programmed/pre-planned trajectories and/or surgeries. In one exemplary embodiment, the robotic surgical system can move automatically based on sensor data and artificial intelligence.

BRIEF DESCRIPTION OF THE FIGURES

The Foregoing and Other Objects, Aspects, Features, and Advantages of the Present Disclosure Will Become More Apparent and Better Understood by Referring to the Following Description Taken in Conjunction with the Accompanying Drawings, in which:

FIG. 1 is an illustration of drilling a hole using anti-skiving technology and drilling a hole without using anti-skiving technology;

FIGS. 2A-2C illustrate a trajectory snap feature;

FIGS. 3A-3C illustrate a universal instrument guide and associated method of use;

FIGS. 4A and 4B illustrate a hole being drilled in bone using real-time compensation;

FIGS. 5A-5E illustrate robotic guiding of surgical instruments; and

FIG. 6 illustrates a flowchart providing the operational features of the invention according to one exemplary embodiment.

The features and advantages of the present disclosure will become more apparent from the detailed description set forth below when taken in conjunction with the drawings, in which like reference characters identify corresponding elements throughout. In the drawings, like reference numbers generally indicate identical, functionally similar, and/or structurally similar elements.

DETAILED DESCRIPTION OF THE DRAWINGS

The present application incorporates by reference in its entirety the contents of U.S. patent application Ser. No. 14/266,769, filed Apr. 30, 2014, entitled "Apparatus and Systems for Precise Guidance of Surgical Tools"; U.S. patent application Ser. No. 14/602,627, filed Jan. 22, 2015, entitled "Sterile Drape and Adapter for Covering a Robotic Surgical Arm and Preventing Contamination of a Sterile Field"; U.S. patent application Ser. No. 14/695,154, filed Apr. 24, 2015, entitled Surgical Instrument Holder for use with a Robotic Surgical System"; U.S. Patent Application No. 62/395,795, filed Sep. 16, 2016, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue"; U.S. Patent Application No. 62/278,313, filed Jan. 13, 2016, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue"; U.S. patent application Ser. No. 14/799,170, filed Jul. 14, 2015, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue."

Among other things, the disclosed technology relates to intra-operative planning of surgeries using robotic surgical systems and haptic control. Examples of such a system are described in U.S. patent application Ser. No. 14/266,769, filed Apr. 30, 2014, entitled "Apparatus and Systems for Precise Guidance of Surgical Tools", the contents of which are hereby incorporated by reference in its entirety.

Furthermore, the disclosed technology includes methods and systems for stabilizing the robotic surgical system on the operation room floor. Additionally, the disclosed technology includes various components utilized in or with the robotic surgical system, such as a sterile drape and an instrument holder. A sterile drape for use with the disclosed technology is described in U.S. patent application Ser. No. 14/602,627, filed Jan. 22, 2015, entitled "Sterile Drape and Adapter for Covering a Robotic Surgical Arm and Preventing Contamination of a Sterile Field", the contents of which are hereby incorporated by reference in its entirety. An example instrument holder that can be used with the disclosed technology is described in U.S. patent application Ser. No. 14/695,154, filed Apr. 24, 2015, entitled Surgical Instrument Holder for use with a Robotic Surgical System", the contents of which are hereby incorporated by reference in its entirety.

The present application relates to robotic surgical systems for assisting surgeons during spinal, neuro, and orthopedic surgery. The disclosed technology provides surgeons with the ability to perform precise, cost-effective robotic-assisted surgery. The disclosed technology may improve patients' outcome and quality of life as well as reduce the radiation received by the operation room team during surgery.

In one exemplary embodiment, a surgical robotic system provides haptic steering and force feedback and integrates with existing standard instruments. In another exemplary embodiment, the surgical system can be integrated with existing surgical methods, including open, minimally invasive, or percutaneous procedures with or without assistance of a navigation system.

FIG. 1 is an illustration of using anti-skiving technology to improve hole placement accuracy. Skiving occurs when drill bit goes off the trajectory due to drilling at an angle different than the right angle to the surface. Skiving is a well-known and documented problem for robots used in surgery, such as spinal surgery. The disclosed technology, including the robot, control system and specially designed drill bit, enables skiving to be practically removed. Examples of this technology are described in U.S. Patent Application No. 62/395,795, filed Sep. 16, 2016, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue", U.S. Patent Application No. 62/278,313, filed Jan. 13, 2016, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue", and U.S. patent application Ser. No. 14/799,170, filed Jul. 14, 2015, entitled "Anti-Skid Surgical Instrument for use in Preparing Holes in Bone Tissue", the contents of each of which are hereby incorporated by reference in their entirety. Anti-skiving (also referred to as anti-skid) technology can be used in robotic surgery, with difficult patient anatomy, and for revision surgeries.

The present disclosure provides a surgical robot that includes a robotic arm mounted on a mobile cart. An actuator may move the robotic arm. The robotic arm may include a force control end-effector configured to hold a surgical tool. The robot may be configured to control and/or allow positioning and/or movement of the end-effector with at least four degrees of freedom (e.g., six degrees of freedom, three translations and three rotations).

In some implementations, the robotic arm is configured to releasably hold a surgical tool, allowing the surgical tool to be removed and replaced with a second surgical tool. The system may allow the surgical tools to be swapped without re-registration, or with automatic or semi-automatic re-registration of the position of the end-effector.

In some implementations, the surgical system includes a surgical robot, a tracking detector that captures the position of the patient and different components of the surgical robot, and a display screen that displays, for example, real time patient data and/or real time surgical robot trajectories.

In some implementations, a tracking detector monitors the location of patient and the surgical robot. The tracking detector may be a camera, a video camera, an infrared detector, field generator and sensors for electro-magnetic tracking or any other motion detecting apparatus. In some implementation, based on the patient and robot position, the display screen displays a projected trajectory and/or a proposed trajectory for the robotic arm of robot from its current location to a patient operation site. By continuously monitoring the patient and robotic arm positions, using tracking detector, the surgical system can calculate updated trajectories and visually display these trajectories on display screen to inform and guide surgeons and/or technicians in the operating room using the surgical robot. In addition, in certain embodiments, the surgical robot may also change its position and automatically position itself based on trajectories calculated from the real time patient and robotic arm positions captured using the tracking detector. For instance, the trajectory of the end-effector can be automatically adjusted in real time to account for movement of the vertebrae or other part of the patient during the surgical procedure.

Now turning to drawings, FIG. **1** illustrates entry holes created by a standard drill bit and an enhanced drill bit according to one embodiment of the present application. In this exemplary embodiment, an enhanced drill bit is provided which creates an entry hole **12** that is generally larger than non-enhanced drill bill. The enhanced drill bit provides anti-skiving features and produces a larger entry hole to minimizes errors that may occur during surgery causing by skiving.

FIGS. **2**A-**2**C illustrate a surgical robotic system that includes a robot arm **14**, and an end effector **16** that is positioned over a patient. In one embodiment, there is a trajectory "snap" feature that allows optimal positioning of the end effector **16** on a preferred trajectory. In certain embodiments, a surgeon must move the robotic arm **14** so that the end effector **16** is near the desired trajectory for the operation. Rather than have the surgeon perfectly alight the end-effector with the trajectory, the robot arm **14** can move the end-effector **16** so that it is appropriately positioned relative to the trajectory once the end-effector is within a threshold distance of the trajectory.

In certain embodiments, once the end-effector **16** is within a threshold distance of the desired trajectory, the robotic surgical system may automatically move (e.g., at a pre-programmed pace) the end effector **16** such that the end-effector is appropriately positioned along the trajectory. The threshold distance can be greater than zero (e.g., greater than 0.1 cm, 0.5 cm, or 1 cm) and less than 1 meter (e.g., less than 20 cm, 10 cm, 5 cm, 3 cm).

In manual surgery, the trajectory has to be found four times: before incision, when drilling, when tapping, and when placing screw. Using the disclosed technology, the trajectory is found once and can be maintained or a new trajectory may be used. The disclosed technology, in certain embodiments, assists a user in quickly finding trajectories in space using guiding forces (like gravity or virtual spring). Trajectories can also be planned using navigation techniques and may be downloaded from navigation, planned manually, or planned automatically. The surgeon can at any time fine-tune the trajectory using haptic control. This provides significant potential for time saving in deformity cases.

FIGS. **3**A-**3**C illustrates a surgical robotic system that includes a robot arm **20**, and a universal instrument guide **22** and associated methods of use. FIG. **3**A is an illustration of a drill bit **24** being inserted into the guide **22** held by the robot arm **20** to drill a hole in a bone. Anti-skiving technology as described above can be used for drilling. Next, as shown in FIG. **3**B, a tap **26** is used to prepare/create threads in the hole. Finally, as shown in FIG. **3**C, an instrument **26** is used to place a screw in the tapped hole. This can be accomplished using the disclosed technology without the need for a k-wire. Accordingly, a user can drill, tap and place a screw through the same access channel.

FIGS. **4**A and **4**B illustrate real-time compensation of the robot arm based on the tracking of optical markers positioned on instruments during the surgical procedure. Specifically, real-time compensation allows the instrument to track the movement of the vertebra. In some situations, the vertebra can move when forces are applied, such as while drilling a hole. In one exemplary embodiment, the robot arm follows the movement of the vertebra in real time using navigation techniques.

In one embodiment, as movement of the vertebra is detected and the robot arm automatically adjusts the position of the instrument based on this detected movement. This feature allows the planned or set trajectory to be maintained.

Specifically, FIG. **4**A illustrates the vertebra **30** of a patient and tracking device **32** in a first position and the drill **34** in a first position. As shown in FIG. **4**B, the vertebra **30** has moved to a second position and the drill **34** has moved to a corresponding second position automatically based on the tracking of the patient and the instruments. This technique can be used in many surgeries, particularly surgeries that will encounter highly mobile vertebrae, such as cervical and trauma surgeries. In other embodiments, as the vertebra is moved either accidentally or purposefully, the robotic system automatically calculates the movement of the vertebra based on movement and registration of the tracking device **32**. Using the monitored movement of the vertebra, the robotic system then automatically causes the robot arm to move to the planned trajectory based on the second position of the vertebra.

FIG. **5**A illustrates a user planning a trajectory. In one embodiment, there is a robotic arm **40** coupled to a base **42**. The robotic arm **40** includes an end effector **44** that is configured to receive an instrument **46** for performing surgical procedures. A user can move the robotic arm **40** with the instrument **46** (e.g., pointer) held by the end-effector **44** to a desired trajectory. The user can then select to have the particular trajectory saved by within a computer processor of the robotic surgical system. Alternatively, the trajectory can be obtained through real-time navigation or tracking of the instrument **46** and the patient through the use of optical markers. As shown in FIG. **5**B, in certain embodiments, the vertebra can be punched with an instrument **46** such as an awl. As shown in FIG. **5**C, the hole is drilled and tapped to prepare for insertion of a screw. In certain embodiments, as shown in FIG. **5**D, the robot arm is in trajectory-lock mode and follows the advancement of an instrument **46**. This can be accomplished by measuring the force applied to the instrument by the user via a force sensor coupled at the end effector and moving the robotic arm in accordance with this force. The force sensor is configured to sense and measure all forces applied to the end effector. These force sensor is capable of measuring forces in the x, y, and z directions. Next, as shown in FIG. **5**E, a screw is placed in the tapped hole. In other embodiments, the instrument **46** may be a drill, a tap, k-wire or anything instrument **46** suited to be used for a particular spinal procedure.

FIG. **6** illustrates a flow chart of the feedback system according to one exemplary embodiment of the present application. A user provides a planned trajectory **60** for positioning the robot arm and end effector through the use of navigation techniques. In one exemplary embodiment the planned trajectory is the directional position of the end effector so that a pedicle screw may be placed in the vertebra. In other embodiments, the planned trajectory may align the end effector so that an intervertebral spacer may be positioned through the end effector in the intervertebral space of adjacent vertebral bodies. In another embodiment, the planned trajectory may align the end effector so that a bone plate may be positioned on adjacent vertebral bodies. In other embodiments, the planned trajectory may be a procedure such a biopsy, a discectomy, bone graft implementation, kyphoplasty, vertebroplasty.

Turning back to FIG. **6**, once the planned trajectory is provided to the computer system operating the robotic arm, the system continuously checks the position of the end effector with planned trajectory positions and provides a graphical image **64** of the planned positioning of the end effector and the actual positioning of the end effector. The variance **66** between the planned trajectory and actual positioning of the end effector and the patient is calculated and imaged to the user. If the variance is less than a threshold distance **68**, then robot arm remains unmoved from the planned trajectory and the computer system rechecks the position of the end effector **62** in view of the patient. If the variance is greater than a threshold distance **70**, the feedback system will signal the actuator of the robot arm to move the end effector to the planned trajectory based on the position of the patient and the instruments that are navigated by the optical system. In some embodiments, if the patient is moved accidentally, the threshold variance will be greater than the planned trajectory variance and the robot arm will move the end effector to the new trajectory that is within the threshold distance. In one exemplary embodiment, the threshold distance may be greater than 0.1 cm, 0.5 cm, or 1 cm or less than 1 meter (less than 20 cm, 10 cm, 5 cm, 3 cm). In certain embodiments, the robotic surgical system continuously checks the threshold distances in real-time. In other embodiments, the user may input a number of reviews of the threshold distances to minimizes robotic arm movements.

In certain embodiments, the disclosed technology is used for volume removal. For example, the disclosed technology can be used for orthopedic surgery, such as unilateral knee replacement. No-go zones, such as locations of nerves and tendons, can be defined before the procedure is performed. Stay-in zones (volume for implant placement—"negative" of the implant) can also be defined. A surgeon can manipulate the robot, directly or remotely, to perform the robot. However, the robot can ensure that the instrument used attached to the end-effector does not enter a no-go zone remains within a stay-in zone. This provides quick and precise implant placement in accordance with planning. Furthermore, the system can be fully interactive such that the surgeon remains in control the entire time.

In certain embodiments, the disclosed technology can be used for rod bending. For example, the system can bend rods for use in deformity cases. The system provides quick, easy and automatic rod bending to create the appropriately shaped rod. The desired shape can take into consideration target sagittal balance and actual pedicle screw placement. The system can also provide a small bending radius even when the rod is formed of the hardest materials. In certain embodiments, the robot is "locked" to particular rods only. The rod bending system provides significant time savings and usability improvements.

In view of the structure, functions and apparatus of the systems and methods described here, in some implementations, a system and method for providing a robotic surgical system are provided. Having described certain implementations of methods and apparatus for supporting an robotic surgical systems, it will now become apparent to one of skill in the art that other implementations incorporating the concepts of the disclosure may be used. Therefore, the disclosure should not be limited to certain implementations, but rather should be limited only by the spirit and scope of the following claims.

Throughout the description, where apparatus and systems are described as having, including, or comprising specific components, or where processes and methods are described as having, including, or comprising specific steps, it is contemplated that, additionally, there are apparatus, and systems of the present invention that consist essentially of, or consist of, the recited components, and that there are processes and methods according to the present invention that consist essentially of, or consist of, the recited processing steps.

It should be understood that the order of steps or order for performing certain action is immaterial so long as the invention remains operable. Moreover, two or more steps or actions may be conducted simultaneously.

What is claimed is:

1. A method for performing robotic-assisted surgery, the method comprising:
- providing a robot surgical system including:
  - a robotic arm;
  - an end-effector configured to hold a first surgical tool;
  - an actuator to move the robotic arm and position the end-effector;
  - optical tracking markers configured to be attached to the end-effector and a patient;
  - an optical tracking detector configured to track the position of the optical tracking markers; and
  - a processor,
- providing a virtual representation of the patient;
- continuously obtaining the end-effector position and the patient position from the optical tracking detector, while a surgeon is manually moving the end-effector;
- determining whether the manually moving end-effector is within a threshold distance of a planned positioning and if within the threshold distance, automatically move the robotic arm to align the end effector with the planned positioning;
- continuously calculating a variance between the planned positioning and an actual positioning of the end-effector;
- providing on a display device a graphic image of the planned positioning and the actual positioning of the end-effector; and
- controlling the actuator to move the end-effector to the planned positioning based on the actual positions of the patient and the first surgical tool if the calculated variance is greater than the threshold distance.

2. The method of claim **1**, further comprising:
- determining whether the first surgical tool is within the threshold distance of a pre-planned trajectory; and
- moving the robotic arm such that the first surgical tool is appropriately aligned with the pre-planned trajectory.

3. The method of claim **2**, wherein the threshold distance is greater than zero and less than 20 cm.

4. The method of claim **2**, wherein the threshold distance greater than 0.1 cm and less than 20 cm.

5. The method of claim **2**, wherein the threshold distance is greater than 1 cm and less than 3 cm.

6. The method of claim **2**, wherein the threshold distance is greater than 0.5 cm and less than 5 cm.

7. The method of claim **1**, wherein the end effector is configured to receive a second surgical tool for performing surgical procedures.

8. The method of claim **1**, wherein the first surgical tool is a drill bit.

9. The method of claim **1**, wherein the first surgical tool is an awl.

10. The method of claim **1**, wherein the first surgical tool is used to position a pedicle screw in bone.

11. The method of claim 1, wherein the first surgical tool includes optical markers for tracking by the optical tracking detector.

12. A method for performing robotic-assisted surgery, the method comprising:

providing a robot surgical system including:

a robotic arm;

an end-effector attached to the robotic arm and configured to hold a first surgical tool, the end-effector having an optical tracking marker;

an optical tracking marker array configured to be attached to a patient;

an actuator for-controlling movement of the robotic arm and the end-effector;

an optical tracking detector; and

a feedback system,

continuously detecting the position of (i) the end-effector position and (ii) patient position by detection of the optical marker attached to the end-effector and optical marker array attached to the patient, while a surgeon is manually moving the end-effector; and

determining whether the manually moving end-effector is within a threshold distance of a planned positioning and if within the threshold distance, automatically move the robotic arm to align the end effector with the planned positioning;

continuously calculating, via the feedback system, a variance between the planned positioning and actual positioning of the end-effector based on output from the optical tracking detector, and

controlling, via the feedback system, the actuator to move the end-effector to the planned positioning based on the actual positions of the patient and the first surgical tool if the calculated variance is greater than the threshold distance.

13. The method of claim 12, wherein the feedback system, includes a force sensor that calculates the movement of the end effector away from the planned positioning and moves the robotic arm such that the first surgical tool is aligned with a planned trajectory.

14. The method of claim 12, wherein the threshold distance is greater than zero and less than 20 cm.

15. The method of claim 12, wherein the threshold distance greater than 0.1 cm and less than 20 cm.

16. The method of claim 12, wherein the threshold distance is greater than 1 cm and less than 3 cm.

17. The method of claim 12, wherein the threshold distance is greater than 0.5 cm and less than 5 cm.

* * * * *